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Controlling Sulfate Attack in Mississippi Department of Transportation Structures

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Abstract At some construction sites in Mississippi, deterioration of concrete in contact with the surrounding soil could be related to the high sulfate content of the adjacent soils. Studies dating to 1966 have documented sulfate attack associated with specific types of sulfide or sulfate-rich soils. Future highway-related construction must include specified procedures and materials that will ensure the service life of concrete construction is not reduced by such aggressive soils.

In this project, three portland cements and five pozzolans, which can be used as cement replacements, were investigated to determine which of these cements and/or cement blends could be categorized as sulfate-resistant. Two screening procedures, the University of California Pavement Research Center's Caltrans rapid sulfate test and the American Society for Testing and Materials' Standard C1012 (standard test method for length change), were used to evaluate the cements/blended cements. Results from the Caltrans test identified only one of the blended cements investigated that failed to qualify as sulfate resistant. The results from the bar expansion test (ASTM C1012) indicated that only one cement evaluated would not meet the criterion for an American Concrete Institute (ACI) Class 1 sulfate-resistant cement.

Further screening was done by examining the expansion trends and the conditions of the test bars after 1 year. Eight cements or blended cements could be judged on the basis of no or slow tendency to show change dimensions and no discernible damage to the mortar test bars after 1 year of exposure. All of the cements performed well in this test program when blended with silica fume.

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Preface

The research reported herein was conducted by personnel of the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. Dr. Charles A. Weiss, Jr., ERDC Geotechnical and Structures Laboratory (GSL), was the Principal Investigator. This report was prepared by Dr. Weiss, Dr. Toy S. Poole, Dr. Philip G. Malone, Melvin C. Sykes, Joe G. Tom, Brian H. Green, and Billy D. Neeley.

The study was sponsored by the Mississippi Department of Transportation Research Division, under State Study 194.

The work was accomplished under the general supervision of Toney K. Cummins, Chief, Concrete and Materials Branch (CMB); Dr. Larry N. Lynch, Chief, Engineering Systems and Materials Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

Summary

At some construction sites in Mississippi, deterioration of concrete in contact with the surrounding soil could be related to the high sulfate content of the adjacent soils. Studies dating to 1966 have documented sulfate attack associated with specific types of sulfide or sulfate-rich soils. Future highway-related construction must include specified procedures and materials that will ensure that the service life of concrete construction is not reduced by such aggressive soils.

Detailed soil surveys that include a determination of the sulfide and sulfate content of the soil can highlight areas that have these potentially aggressive soils. Proper soil excavation and soil handling and selection of sulfate-resistant materials for concrete production can improve these soil-concrete incompatibility problems.

A key element in the planning of projects that may be subject to sulfate attack is the selection of cements or blended cements that are acid resistant without the addition of mineral admixtures. Typical sulfate attack involves the reaction of dissolved sulfates in the soil with the aluminum-rich phases in cement paste. The usual result is the growth of hydrated aluminum sulfates, such as ettringite, which produces crystallization pressure in the pore space of the concrete. This increased pore pressure can produce expansion and cracking, which in turn can result in the loss of strength of the concrete and spalling.

In this project, three portland cements and five pozzolans that can be used as cement replacements were investigated to determine which of these cements and/or cement blends could be categorized as sulfate resistant. Two screening procedures, the Caltrans rapid sulfate test and the ASTM C1012 standard test method for length change, were used to evaluate the cements/blended cements.

Results from the Caltrans test identified only one of the blended cements investigated that failed to qualify as sulfate resistant. That was a blend of Type I-II cement from Buzzi Unicem Corporation's Cape Girardeau, MO, plant and a Class C fly ash obtained from Bayou Ash from the New Roads, LA, power plant.

The results from the bar expansion test (ASTM C1012) indicated that only one cement—that from the Holcim's Artesia, MS, plant—used either alone or with a metakaolin, would not meet the criterion for an American Concrete Institute (ACI) Class 1 sulfate-resistant cement.

Further screening was done by examining the expansion trends and the conditions of the test bars after 1 year. Eight cements or blended cements could be judged on the basis of no or slow tendency to show change dimensions and no discernible damage to the mortar test bars after 1 year of exposure. Only the Type I-II cement from Buzzi Unicem Corporation's Cape Girardeau plant showed a high-degree of sulfate resistance when used alone with no pozzolan as cement replacement. All of the cements performed well in this test program when blended with silica fume. Acceptable blended cements were also developed using the Type I-II cements (both Buzzi Unicem Corporation's cement) if either slag or Class F fly ash was used as a cement replacement. While metakaolin typically was not successful in producing sulfate resistance, it did perform satisfactorily with the Type I-II cement from Buzzi Unicem Corporation's Cape Girardeau plant.

It should be possible to address the problem of increasing the service life of concrete structures built in, or on, sulfate-rich soils in Mississippi, by surveying each proposed construction site for the presence of sulfides or sulfates in the soil, developing plans for excavation and replacement of aggressive soils, and using cements or blended cements that are sulfate-resistant in the production of concrete that will be exposed to aggressive soils.

1 Introduction

Background

Sulfate in soil and/or in water surrounding the concrete can interact with concrete in a number of ways that result in the loss of strength and the production of cracking in the concrete. Some disagreement can be found in the literature as to the manner in which the interaction between sulfates and concrete occurs and as to the factors that influence the sulfate reactions that produce concrete deterioration.

Although some scientists have extensively debated the source of sulfate, the scientific community recognizes the associated deterioration of concrete. Conventional portland cement concrete can deteriorate when exposed to alkaline caused by alkali sulfate solutions. The major mineral formed by the sulfate-concrete interaction is ettringite ($C_6AS_3H_{32}$). Ettringite is one of the materials that normally forms during the early setting of portland cement from a reaction between calcium aluminate and gypsum in the curing cement paste. The formation of ettringite from its constituent materials involves an increase in volume of 9.37% (Skalny et al. 2002). In the case where ettringite forms before the cement paste has gained strength, the increase in the volume can be accommodated without producing cracking. If ettringite forms after the paste has gained strength, the crystallization can cause cracking (Wolter 1997).

One source of confusion relates to whether the effects observed from interaction with sulfate are physical or chemical. Some investigators point out that the sulfate compounds can simply form crystals in the pore spaces of the concrete—which produces cracking due to crystalline sulfate compounds growing or ripening in voids and develops stress that causes cracks in the surrounding concrete (Hime and Mather 1999; Skalny et al. 2002; Collepardi 2003). Most investigators agree that there is a “physical salt-weathering mechanism” but that chemical interaction of sulfate with the compounds present in concrete is part of the damaging interaction. In the chemical interaction, it is the transformation of the compounds in the concrete and sometimes the loss of reacted soluble components that causes the loss of strength in the concrete.

The effects observed are most probably due to both physical and chemical mechanisms that can be occurring at the same time in the concrete. The presence and abundance of specific compounds in the concrete, such as calcium aluminates and calcium hydroxide, can influence the degree of damage observed. In all cases, the deterioration observed appears to be related to the reaction of phases in the concrete as well as additional chemical reactions caused by infiltration of sulfate along with other counterions, such as calcium, magnesium, or sodium.

Additionally, there are well-documented cases of concrete deterioration due to acid sulfate attack resulting from acidic soil, water, or groundwater. Acidic soils can be produced by the oxidation of sulfides in the soil, and this condition can be extremely detrimental in that it results in dissolution of constituents in the concrete and in the formation of expansive crystalline compounds that cause cracking (BRE Construction Division 2005).

Scope and objectives

Historically, sulfate attack on concrete structures in the state of Mississippi has been of little concern in the concrete industry, because the sulfate concentrations have been assumed to be relatively low. The Mississippi Department of Transportation (MDOT) has historically required the use of ASTM C150 Type II cement and determined this measure to provide adequate control of concrete deterioration from any sulfates that might be present. However, two events have occurred that have created a need to re-examine this problem: (1) one of the principal portland cement producers used by MDOT has ceased production of ASTM C150 Type II cement, and (2) evidence has recently been discovered that indicates higher concentrations of sulfates may be present at depth in some areas of Mississippi. This creates concern for the long-term durability of concrete pilings.

Chemistry of concrete and sulfate attack

Concrete is a complex composite material consisting of a paste fraction (comprising portland cement and fine aggregate) that holds a coarse aggregate together to form the concrete mass. The composition of concrete can vary widely, primarily because the coarse and fine aggregates are generally locally derived. Variation in the type of cement used and in the mineral admixtures (such as slag or fly ash) and the additives (water-reducing admixtures, retarding admixtures, air-entraining admixtures) employed can further complicate the mixture. The nature of the sulfate

attack (internal or external, acid or alkaline) determines the components in the concrete that are affected and the nature of the damage that occurs.

Where sulfate occurs as an infiltration of sulfate-rich water in the pore spaces of the concrete, damage is thought to occur through the reaction of the sulfate ions with aluminum silicate compounds in the paste fraction. The reaction can be described as follows:

$$6Ca^{2+} + 3SO_4^{\ 2-} + Al_2O_6^{\ 6-} + 32\,H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 32\,H_2O$$

The components in the reaction may occur as ions in solution, or they may be solid reactants (such as the aluminum compounds) that react on the surface only (topochemical reactions). While the ettringite reaction, shown above, is considered to be the major reaction that results in a volume increase and weakening of the concrete, other researchers have pointed out that gypsum formation may also be a part of expansive sulfate attack. The problem of determining the cause of the concrete weakening is further complicated by the occurrence of external acid attack on concrete that may also form gypsum and can appear to be an expansive gypsum reaction from the components inside the concrete (Hime and Mather 1999).

Record of sulfate attack in Mississippi

Problems with the deterioration of concrete pavement were noted by the Testing Division of the Mississippi State Highway Department as early as the 1950s. In the 1960s, removal and examination of damaged concrete from pavement that was installed over soils known to contain high levels of sulfate showed mineralogical evidence that calcium alumino-sulfate minerals such as ettringite were present in significant quantities (Lossing 1965). The areas in Mississippi where concrete deterioration associated with sulfate were observed, and the areas where sulfates have been reported to be abundant, are shown in Table 1. Additional concerns have arisen because of the need to install deep cast-in-place concrete footings for bridges and overpasses.

Unlike the western states, which are drier, Mississippi does not have evaporative buildup of sulfates in the soil. The sulfate in Mississippi comes from the oxidation of sulfide minerals that are present in the newer peat-rich soils and in the older surficial geologic deposits. The recent deltaic

Table 1. Locations in Mississippi with documented sulfate-attack problems.

General Location	Source of Problem	Reference
Northeastern MS, Tennessee-Tombigbee Waterway	Pyrite rich soil from the Eutaw Fm.	Ammons et al. 1991; Jones 2000
South-southwestern MS-eastern LA	Pyrite-rich back swamp soils	Aslan and Autin 1996
Chickasaw Co.	Porter's Chapel Fm.	Lossing 1965
Lee Co.	Coffee Sand, Mooreville Chalk	Lossing 1965
Itawamba Co.	Coffee Sand, Mooreville Chalk	Lossing 1965
Lauderdale Co.	Zilpha, Winona, and Tallahatta Fm.	Lossing 1965
Issaquena Co.	Sharkey Clay	Lossing 1965

deposits are known to contain finely divided, amorphous iron sulfide from decomposing plant materials. The older geologic sulfides are well-crystalline minerals related to pyrites and marcasites (FeS_2) that formed during the Tertiary marine sediments in the Mississippi Embayment.

In some areas of Mississippi, the determination of the amount of sulfate in the soil or groundwater may not be as important in estimating the possible extent of sulfate damage as knowing the amount of potential sulfate production represented in the unoxidized iron sulfides in the soil. Disturbing the soil by excavating to install concrete footings and lay down concrete pavement may be the most important factor in exposing the buried sulfides to air, so they can be oxidized to form acidic sulfate compounds that can aggressively attack the later in-place concrete.

Developing strategies for predicting and improving sulfate attack when the sulfide oxidation is a critical factor in the process would involve using nonstandard test procedures. Similarly, nonstandard corrective techniques may have to be used such as treating the soil or tailoring the chemistry of the concrete to address sulfate attack.

Controlling sulfate attack in MDOT structures

The following approaches have been used to control sulfate attack:

1. Managing the site to reduce the production of an aggressive sulfate environment (Byerly 1990, 1996; Thomas et al. 2003)

2. Selecting cements that are low in sulfate-reactive components such as the low-calcium aluminate cements (Chen and Odler 1992; Shanahan and Zayed 2007)
3. Blending mineral additives with an available cement to increase its sulfate resistance. The additives typically include fly ash, ground granulated blast furnace slag (GGBFS), silica fume, or metakaolin (Stark 1990; Al-Amoudi 2002; Al-Dulaijan et al. 2003; Binici and Aksogan 2006).

Particular attention must paid to the conditions at the concrete placement site in areas where it is suspected that sulfate attack will occur due to an external source of sulfate migrating into the concrete. Managing soils onsite, in such a way as to minimize the likelihood of severe sulfate attack, may include measures such as selecting backfill that will be placed adjacent to buried concrete or adding lime to soil to raise the pH and neutralize any acid. Sometimes even local groundwater management may be of use (BRE 2005).

Proportioning guidelines for concretes that will be exposed to sulfate-containing solutions have been established by the ACI (2004). These guidelines specify the use of specific types of cement or blended cements, the water-cementitious materials ratio, and the minimum unconfined compressive strength that should be used at particular levels of sulfate exposure (Table 2).

Table 2. ACI requirements for concrete exposed to sulfate containing solutions.

Rank of Sulfate Exposure	Water Soluble Sulfate (SO_4) in Soil (wt %)	Sulfate in Water (ppm)	Cement Type	Water-to-Cementitious Material Ratio	Minimum Unconfined Compressive Strength (psi)
Negligible	$0.00 \leq SO_4 < 0.10$	$0 \leq SO_4 < 150$	Not specified	Not specified	Not specified
Moderate	$0.10 \leq SO_4 < 0.20$	$150 \leq SO_4 < 1{,}500$	II, IP(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	4,000
Severe	$0.20 \leq SO_4 \leq 2.0$	$1{,}500 \leq SO_4 \leq 10{,}000$	V	0.45	4,500
Very Severe	$SO_4 > 2.00$	$SO_4 > 10{,}000$	V plus pozzolan	0.45	4,500

Note: To convert pounds (force) per square inch to kilopascals, multiply by 6.894757.

When only Type I cement is used, developing sulfate resistance depends on selecting the proper mineral admixture that can be added to the concrete to produce the minimum expansion on exposure to a high-sulfate solution. The ASTM standard requirement for a sulfate-resistant blended

cement is that the blend, when subjected to the ASTM C1012 test procedure, should show less than 0.10% maximum expansion for a moderate sulfate resistant rating and 0.050% for a high sulfate resistant rating after a 180-day exposure.

The present investigation is directed toward determining if cements and mineral admixtures available in Mississippi can be proportioned to produce sulfate-resistant concrete. The goal is to produce a sulfate-resistant blended cement that can be used to produce durable concrete with the least logistical burden. Ideally, this approach will allow ready-mix plants to adapt to production of sulfate-resistant concrete while avoiding the need either to change their material sourcing or to increase their storage and blending capabilities.

2 Methods and Materials

Selection of cement and mineral additions

Cements from three sources were separately blended with a single mineral admixture (pozzolan) to make 15 blended cement types. The mineral admixtures were obtained from two Class F fly ash sources, one Class C fly ash source, two slag (GGBFS) sources, one silica fume source, and one metakaolin source. The materials and the sources are given in Table 3.

Table 3. Sources of cements and mineral admixtures.

Material	Source	Location	Designation
Type I Portland Cement	Holcim Corp.	Artesia, MS	Artesia
Type I-II Portland Cement	Buzzi Unicem USA, Inc.	Signal Mountain, Chattanooga, TN	Buzzi (Sig Mtn)
Type I-II Portland Cement	Buzzi Unicem USA, Inc.	Cape Girardeau, MO	Buzzi (Cape G)
Fly Ash Class F	Headwaters Resources, Inc (ISG)	Woodstock, GA	ISG
Fly Ash Class F	Owensboro Municipal Utilities (OMU)	Owensboro, KY	OMU
Fly Ash Class C	Bayou Ash, Inc. New Roads Plant	Baton Rouge, LA	New Roads
Ground Granulated Blast Furnace Slag	Lone Star Industries, Inc.	New Orleans, LA	Lonestar
Ground Granulated Blast Furnace Slag	Holcim	Chicago, IL	Holcim 100
Ground Granulated Blast Furnace Slag	Holcim	New Orleans, LA	Holcim 120
Metakaolin	BASF Corp.	Florham Park, NJ	Metamax®
Silica Fume	Elkem Materials, Inc.	Pittsburgh, PA	ES900W

A listing of materials and the amount of cement replacement in each of the 15 test mixtures is presented as Table 4.

Table 4. Cement and cement replacements for test mixtures.

Mix No.	Cement	Cement Replacement
1	Holcim, Artesia 100%	None
2	Holcim, Artesia, 75%	ISG, 25%
3	Holcim, Artesia, 60%	Lonestar, 40%
4	Holcim, Artesia, 90%	ES900W, 10%
5	Holcim, Artesia, 90%	Metamax®, 10%
6	Buzzi (Sig Mtn), 100%	None
7	Buzzi (Sig Mtn), 75%	OMU, 25%
8	Buzzi, (Sig Mtn), 60%	Holcim 120, 40%
9	Buzzi (Sig Mtn), 90%	ES900W, 10%
10	Buzzi (Sig Mtn), 90%	Metamax®, 10%
11	Buzzi (Cape G.), 100%	None
12	Buzzi (Cape G.), 75%	New Roads, 25%
13	Buzzi (Cape G.), 60%	Holcim 100, 40%
14	Buzzi (Cape G.), 90%	ES900W, 10%
15	Buzzi (Cape G.), 90%	Metamax®, 10%

Test methods

Two test methods were selected to assess the sulfate resistance of the mortar prepared with the selected cements and blended cements. The two methods, ASTM C1012 (ASTM 2004) and the Caltrans accelerated test (Monteiro et al. 2000), are complementary in that each method addresses durability issues that are ignored by the other when the two test methods are used separately.

ASTM C1012 – standard test method for length change of hydraulic-cement mortars exposed to a sulfate solution

The ASTM C1012 test measures the expansion of a mortar bar immersed in a sodium sulfate solution. The test was developed to address problems with the earlier ASTM C452 test (ASTM 1968) that used a mortar prepared by mixing calcium sulfate into the mortar when the bar was prepared. The objection to the ASTM C452 test was that the reaction between the sulfate and the cement was so rapid that the effect of the slower reactions between the cement and the pozzolan admixtures did not have time to occur. Both of these ASTM tests have incurred objections because they measure only length change and are very sensitive to specimen size and geometry (Tumidajski and Turc 1995). Also, due to the measurement procedure, softening and spalling during sulfate attack are ignored (Mehta and

Gjorv 1974). The ASTM C1012 test was also considered to require an unnecessarily extended exposure time due to the low concentration of sulfate during some parts of the testing period (Brown 1981; Clifton et al. 1999). The performance criteria for blended cements have been set up for 180-day and 1-year exposure periods under ASTM C595-08 (ASTM 2008). The tests for this investigation were conducted in accordance with ASTM C1012-04. The measurements are detailed in Appendix A.

Accelerated test for measuring sulfate resistance of hydraulic cements for Caltrans LLPRS

The Caltrans LLRPS (Long-life Pavement Rehabilitation Strategies) test (Monteiro et al. 2000) addresses some of the problems that researchers have pointed out in the ASTM tests, in that it uses small (12.7-mm) cubes that provide a higher surface to volume ratio, and it measures sulfate attack in terms of strength loss rather than length change. The Caltrans test is a “go-or-no go” test with the decision to accept the cement or blend as “sulfate-resistant” resting on the ability of the cubes to maintain 75% of their 7-day unconfined compressive strength after a 28-day exposure to a 4% sodium sulfate solution (pH = 7.2). Average strength determinations are used in the calculations, and all averages are based on testing 12 identically prepared and treated samples.

If the data collected from a sample set are considered ambiguous, the test procedure allows for a follow-up test. The additional testing requires the preparation of 36 specimens and strength testing batches of 12, after 7 days curing, and then batches tested after both 28 and 63 days of exposure. In this program, no second phase of testing was undertaken.

For the purposes of this investigation, the Caltrans test was modified to adapt it to the available equipment. A description of the modified test procedure is given in Appendix B. A tabulation of the test results for the 15 mixes used in this investigation is presented in Appendix C.

3 Results and Discussion

Results

The ACI C201-2R classes of exposure severity of cementitious binders for sulfate resistance (ACI 2004), as related to the ASTM C1012 expansion limits, are shown in Table 5.

Table 5. ACI C201-2R equivalence testing of cementitious binders for sulfate resistance.

Exposure Severity	ASTM 1012 Expansion Limit
Class 0 Negligible	--
Class 1 Moderate	0.10% at 6 months
Class 2 Severe	0.05 at 6 months, or <0.10% at 12 months
Class 3 Very Severe	0.10 at 18 months

The criterion for failure in the modified Caltrans rapid sulfate test is given in Appendix B. Samples that fail this test must lose >25% of their 7-day unconfined compressive strength after exposure to the sulfate test solution for 28 days.

Table 6 summarizes and compares the results of the ASTM C1012 tests and the Caltrans test for the 15 cements and cement blends studied in this investigation.

Discussion

Only a single blended cement (Mix 12) failed the modified Caltrans rapid sulfate test. This mix consisted of Buzzi Unicem–Cape Girardeau cement with a 25% replacement of cement with the Bayou Ash from the New Roads Power Plant. The New Roads fly ash is a Class C fly ash. The high calcium content of Class C fly ash often makes it unsuitable for use in concrete that is intended to be sulfate resistant (Thomas et al. 2003; Bhatty and Taylor 2006). Dunstan (1980, 1984, 1987) attributes the low sulfate resistance of concrete and mortar made with Class C fly ash to the fact that Class C fly ashes have a high calcium content, but also have crystalline gehlenite phases that are reactive to sulfate. As a result of 27-year-long study, Dikeou (1970) concluded that the sulfate resistance of

concrete (regardless of type) was increased by the addition of fly ash, but was less effective when Type I cements were used.

Table 6. Level of sulfate resistance from Caltrans rapid sulfate test and ASTM C1012 expansion limit.

Mix No.	Cement	Cement Replacement	Caltrans Acceptance as Sulfate Resistant	ACI C201-2R Class 1 Moderate	ACI C201-2R Class 2 Severe
1	Holcim, Artesia 100%	None	Passed	No	No
2	Holcim, Artesia, 75%	ISG, 25%	Passed	Yes	Yes
3	Holcim, Artesia, 60%	Lonestar, 40%	Passed	Yes	Yes
4	Holcim, Artesia, 90%	ES900W, 10%	Passed	Yes	Yes
5	Holcim, Artesia, 90%	Metamax®, 10%	Passed	No	No
6	Buzzi (Sig Mtn), 100%	None	Passed	Yes	No
7	Buzzi (Sig Mtn), 75%	OMU, 25%	Passed	Yes	Yes
8	Buzzi (Sig Mtn), 60%	Holcim 120, 40%	Passed	Yes	Yes
9	Buzzi (Sig Mtn), 90%	ES900W, 10%	Passed	Yes	Yes
10	Buzzi (Sig Mtn), 90%	Metamax®, 10%	Passed	Yes	Yes
11	Buzzi (Cape G.), 100%	None	Passed	Yes	Yes
12	Buzzi (Cape G.), 75%	New Roads, 25%	Failed	Yes	Yes
13	Buzzi (Cape G.), 60%	Holcim 100, 40%	Passed	Yes	Yes
14	Buzzi (Cape G.), 90%	ES900W, 10%	Passed	Yes	Yes
15	Buzzi (Cape G.), 90%	Metamax®, 10%	Passed	Yes	Yes

Two mixes (Mixes 1 and 5) failed to meet the ACI Class I standard for moderate sulfate resistance. Mix 1 is a Class I portland cement with no cement replacement material. As previously discussed, the Class I cements are considered to have the least sulfate resistance. Mix 5 is the same Type I cement with a 10% replacement using metakaolin (Metamax®). Metakaolin replacements can have a variety of effects on the resulting blended cement. Depending on the chemistry of the cement and the metakaolin, the replacement may or may not improve the sulfate resistance of the concrete (Justice 2005).

The results from the Caltrans rapid sulfate test and the ASTM C1012 bar expansion test suggest that all of the mixes except Mixes 1, 5, and 12 would be useful sulfate-resistant cements or cement blends. However, the trends of the graphed data that were obtained from the ASTM C1012 (Appendix D) test, and the photographs of the test bars made after more than 1 year exposure, suggest that some of the mixtures that were accepted

under the Caltrans rapid sulfate test and the ASTM C1012 bar expansion test may not be the best mixtures for sulfate resistance. The results from examination of the plots and observation of the bars are summarized in Table 7.

Table 7. Expansion trends and 1 year of the ASTM C1012 exposure observations.

Mix No.	Cement	Cement Replacement	Trends of the Plot from the ASTM C1012 Test	Comments on Condition of the Specimens at 1 Year	Remarks
1	Holcim, Artesia 100%	None	Stopped at 120 days	Specimens fell apart	Failed
2	Holcim, Artesia, 75%	ISG, 25%	Upward trend	No cracking	Signs of future failure
3	Holcim, Artesia, 60%	Lonestar, 40%	Modest expansion	Visible cracks	Signs of future failure
4	Holcim, Artesia, 90%	ES900W, 10%	Modest expansion	No cracking	Sulfate resistant
5	Holcim, Artesia, 90%	Metamax®, 10%	Failed at 60 days	Cracked	Failed
6	Buzzi (Sig Mtn), 100%	None	Large expansion	No cracking	Failed
7	Buzzi (Sig Mtn), 75%	OMU, 25%	Modest expansion	No cracking	Sulfate resistant
8	Buzzi (Sig Mtn), 60%	Holcim 120, 40%	Modest expansion	No cracking	Sulfate resistant
9	Buzzi (Sig Mtn), 90%	ES900W, 10%	Modest expansion	No cracking	Sulfate resistant
10	Buzzi (Sig Mtn), 90%	Metamax®, 10%	Large expansion	Cracked	Failed
11	Buzzi(Cape G.), 100%	None	Modest expansion	No cracking	Sulfate resistant
12	Buzzi (Cape G.), 75%	New Roads, 25%	Modest expansion	Significant cracking	Future failure
13	Buzzi (Cape G.), 60%	Holcim 100, 40%	Very modest expansion	No cracking	Sulfate resistant
14	Buzzi (Cape G.), 90%	ES900W, 10%	Very modest expansion	No cracking	Sulfate resistant
15	Buzzi (Cape G.), 90%	Metamax®, 10%	Modest expansion	No cracking	Sulfate resistant

The observations in Table 7 indicate that 8 of the 15 mixes examined would be judged to be sulfate resistant. Options for obtaining successful cements and blended cement are listed below.

1. With the exception of the Buzzi Unicem cement from Cape Girardeau, MO, none of cements would be used as a sulfate-resistant cement without a cement replacement material.
2. The Artesia, MS, cement could be used in a silica fume blend to make an acceptable sulfate-resistant cement.
3. The Buzzi Unicem cement from Signal Mountain, TN, could be used successfully with Class F fly ash, slag, or silica fume.
4. Buzzi Unicem cement from Cape Girardeau could be used without substitution or with slag, silica fume, or metakaolin.

To assess an amount of silica fume that would arrest the expansion of the Artesia, MS, cement when exposed to sulfate, a study of additional data

on incorporation of silica fume was accomplished. Since 10% silica fume proved to be effective in limiting expansion, data on use of silica fume at lower amounts were evaluated. Data provided by MDOT (personal communication) indicated that mixtures made with 5% silica fume replacement failed at 1 year. In addition, data from Al-Dulaijian et al. (2003) on samples made with 7% silica fume and exposed to solutions up to 4% sodium sulfate solutions for up to 2 years showed indications of deterioration as early as 8 months after casting. Their best-performing mixture was one that incorporated 20% of a class F fly ash. Even those samples exhibited some deterioration at 8 months at the highest concentrations of sodium sulfate. As such, it appears that use of 10% silica fume with the Artesia cement is sufficient to prevent failure of the cement according to the ASTM C1012 test method. Given these data, a minimum of 10% silica fume replacement for the cement is needed to pass the ASTM C1012 test method for sulfate resistance.

4 Conclusions and Recommendations

Conclusions

The results of this study lead to the following conclusions:

- A literature survey indicates that, at some locations in Mississippi, the soil sulfate levels are sufficiently elevated so as to put at risk cements that are not designed to be sulfate resistant.
- Sulfide-rich soils that can oxidize to form acid sulfate are also present at some locations in the state and may require special planning during excavation and backfilling for subgrade construction.
- Sulfate-resistant cements can be obtained using a local cement (Buzzi Unicem cement from Cape Girardeau), or sulfate-resistant cements could be made by blending selected cement replacement materials with the other two local cements included in the study (Holcim cement from Artesia, MS, and Buzzi Unicem cement from Signal Mountain, TN).
- The most successful cement replacement material in producing sulfate-resistant blended cements was silica fume.
- Slag and Class F fly ash together, as well as slag by itself, have proved to be useful in improving sulfate resistance with some of the cements included in this study.
- The results from the mixes made with metakaolin indicate that carefully monitored testing with specific cements and metakaolin cement substitutes can be useful in finding a sulfate-resistant blend.

Recommendations

From the overall review of the nature of sulfate attack on concrete highway structures in Mississippi, and the evaluation of data collected from the investigation of sulfate resistance of the selected cements and cement blends, it is possible to suggest the following measures to alleviate the potential problem:

- Site surveys prior to construction should include an evaluation of both the sulfate level in the soil and the potential sulfate production from mineral sulfides in the soil.

- Excavation and soil handling plans that involve the removal of sulfate-rich or potential sulfate-producing soils should be considered as part of the construction program.
- Cement selection should follow the ACI recommendations for using the cement having the lowest aluminum content, often indicated by a high C3A content.
- Construction plans that propose using the cements selected for this study should also include an evaluation of the use of blended cements that incorporate mineral additives such as silica fume, slag, or Class F fly ash. If a cement is used that contains a high aluminum content, 10% addition of silica fume should be used to limit expansion of the cement.
- Planning for preconstruction testing of cements and blended cements should include the ASTM C1012 test program and should be extended for the maximum test interval specified for the test.

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Appendix A: Caltrans Rapid Sulfate Test Procedure

The Caltrans accelerated test for measuring sulfate resistance of hydraulic cements is a method that was developed to select cements and blended cements (cement plus additives) that are suitable for use in high-sulfate environments. In this accelerated test, changes in the unconfined compressive strength of cement paste cubes after sulfate exposure for 28 days are compared to the strength of the same composition cubes after wet curing for 7 days. This test differs from other tests, because the strength, not the expansion, is used to judge the sulfate resistance. Also, this test is conducted on the cement paste, not on a mortar.

Cubes that were approximately 0.5 in. (12.7 mm) on a side were cast using a plastic grid mold; individual molds were not practical due to the time constraints for the project. The cubes were moist cured (100% humidity cabinet at 23°C) for up to 4 days as described in the following paragraph.

The Caltrans test procedure calls for a preliminary assessment of strength using the ASTM C109 Test Procedure to assess the curing time required for the cement to be sufficiently hydrated. Each batch of paste cubes began exposure testing when the C109 test results showed the specimen made with the corresponding cement or cement blend had reached a minimum unconfined compressive strength of 2850 psi (20 MPa). All of the C109 paste cubes prepared with the selected cements or blends reached the target strength within 4 days.

The cubes were exposed to sulfate by immersing them in a 4% sodium sulfate solution. The initial pH of the solution was approximately 7.2. No attempt was made to adjust the pH of the sulfate solution after the cubes were placed in the solution. Sulfate exposure was accomplished by placing the cubes on plastic mesh in tightly closed polyethylene containers.

The unconfined compressive strength (UCS) was determined using a Tinius-Olsen Compression Tester. Samples were tested after 7 and 28 days in a dry condition using the procedure adapted from standard concrete test methods. To compensate for any minor (fraction of a millimeter) variation that could occur in the dimensions of mortar cubes from the

molding grid, each cube was measured prior to unconfined compression testing, and the proper correction for variation in surface area was applied in calculating the unconfined compressive strengths.

The fractional loss in the unconfined compressive strength of the paste cubes after seven days, and then after 28 days, is expressed as the percent loss of strength relative to the 7-day strength. This is shown in the equation below:

$$\Delta f = \frac{f_{28} - f_7}{f_7} * 100$$

where:

Δf = change in strength (percent)

f_{28} = average unconfined compressive strength of cubes after 28-day exposure

f_7 = average unconfined compressive strength of cubes after 7-day exposure.

The criterion for designation of a cement or blend as suitable for use in sulfate-resistant concrete was whether the percent change in strength was less than a 25% decrease.

Appendix B: Caltrans Rapid Sulfate Test Results

Table B1. MDOT/Caltrans cubes 7-day unconfined compressive data (psi).

													Average
Mix 1	3456	3580	3940	3552	2944	2908	2924	3256	3924	3112	2840	3124	3300
Mix 2	2368	2256	2324	2112	1676	2100	2452	3496	2156	2416	1972	2444	2310
Mix 3	2620	3576	2780	2328	3856	3804	2840	3028	3044	2932	2500	3360	3060
Mix 4	2508	4124	3248	3624	4784	5064	4080	3872	3392	4656	3012	3120	3790
Mix 5	3460	2540	4360	3200	2900	3536	4056	4724	3800	4780	3496	3892	3730
Mix 6	3624	4208	4076	3784	4668	3332	4532	3432	3552	4664	4348	4412	4050
Mix 7	2816	3212	3200	2784	3500	2348	3208	3676	3592	2624	2848	3120	3080
Mix 8	2776	3148	3104	2468	3520	3160	2724	3196	2892	2584	2588	3296	2950
Mix 9	2652	3684	3400	3132	3204	3056	4700	2856	3204	3476	3788	3044	3350
Mix 10	3816	4848	5680	4192	4832	4660	3864	3776	2204	5452	4648	5148	4430
Mix 11	2964	2964	2708	3196	2784	3312	2364	2972	2920	3200	2528	3096	2920
Mix 12	4284	3920	3724	3884	3396	3724	4728	2396	3768	3900	3624	3980	3780
Mix 13	2172	2512	2976	2696	2164	3940	3248	2968	3492	2672	3760	3412	3000
Mix 14	4340	4212	5388	5168	4496	3712	4360	4508	5284	4800	4760	4160	4600
Mix 15	3420	2920	4256	3148	3996	4976	3768	4076	2992	3916	4060	2588	3680
Remix 13	2188	2660	2684	2532	2444	2012	1888	2248	1904	2920	2564	2824	2410
Remix 14	5276	4648	4148	4192	4236	6060	4540	4500	3840	3288	4704	4264	4470

Note: To convert pounds (force) per square inch to kilopascals, multiply by 6.894757.

Table B2. MDOT/Caltrans accelerate cubes 28-day unconfined compressive data (psi).

													Average	Caltrans Calculation
Mix 1	4004	4196	3828	3444	4224	4376	5328	4708	3700	5468	3808	4548	4300	30.3
Mix 2	2620	3576	2780	2328	3856	3804	2840	3028	3044	2932	2500	3360	3060	32.5
Mix 3	5160	3648	4756	3932	3256	3632	5312	4688	4524	3964	4392	3904	4260	39.2
Mix 4	3820	5816	4768	3712	5600	5960	4580	3652	4260	5524	5472	4900	4840	27.7
Mix 5	5256	5400	4684	5856	5676	5652	6488	5396	5416	4676	4848	4916	5360	43.7
Mix 6	4836	4640	4756	4968	4220	4708	4716	5920	4404	4212	5264	4584	4770	17.8
Mix 7	3128	4028	4032	3496	3608	4156	3932	3800	3964	3764	4004	4260	3850	25.0
Mix 8	4936	4384	4520	3568	3692	3984	3836	4692	4392	3564	3468	3740	4060	37.6
Mix 9	5816	5668	4888	4792	3996	6336	6416	4868	5756	3156	3452	3644	4900	46.3
Mix 10	5892	5560	7320	6240	7280	5564	6664	5512	6516	6448	5856	5892	6230	40.6
Mix 11	3464	3636	3472	3448	4260	3060	3268	3656	3792	3728	3520	3844	3600	23.3
Mix 12	1896	2276	1904	1832	1596	1448	2272	1952	2136	2180	2612	1868	2000	-47.1
Mix 13	3632	2496	3772	2920	3076	3816	4592	2820	3568	3228	2596	4480	3420	14.0
Mix 14	4384	4364	4820	5340	5224	4152	5156	4360	3432	4572	4196	3892	4490	-2.4
Mix 15	5044	4156	3736	3964	3936	4144	4164	3100	2392	2768	3960	3420	3730	1.4
Remix 13	3604	3148	3528	4200	2964	3728	3812	2384	3324	3240	3656	3232	3400	41.1
Remix 14	4596	5020	4572	3668	4740	3976	3988	3632	5556	4980	4164	5392	4520	1.1

Note: To convert pounds (force) per square inch to kilopascals, multiply by 6.894757.

Appendix C: ASTM C1012 Test Results

Table C1. Length change measurements (% expansion) for mortar mix 1 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	4/17/2008								
Immersed	4/21/2008								
Week 1	4/28/2008	0.01	0.00	0.00	0.00	0.00	0.00	0.004	0.002
Week 2	5/5/2008	0.01	0.01	0.00	0.01	0.01	0.00	0.007	0.005
Week 3	5/12/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.007	0.001
Week 4	5/19/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.008	0.003
Week 8	6/6/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.011	0.003
Week 13	7/21/2008	0.02	0.02	0.02	0.03	0.04	0.02	0.026	0.009
Week 15	8/4/2008	0.03	0.04	0.03	0.06	0.11	0.03	0.050	0.029
Month 4	8/24/2008								
Month 6	10/21/2008								
Month 9	1/20/2009								
Month 12	4/22/2009								

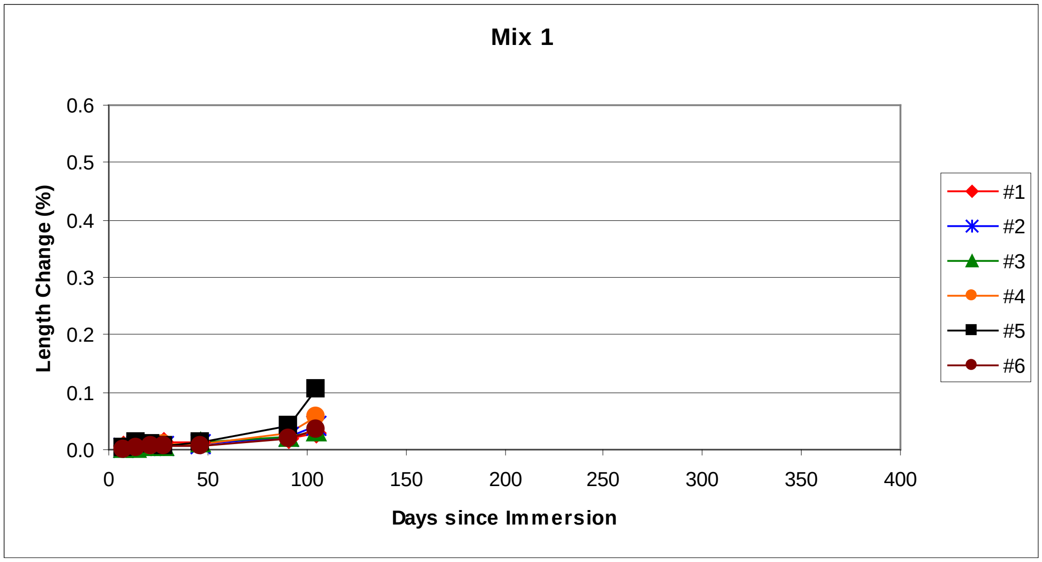

Figure C1. Length change vs. time of exposure for mortar mix 1.

Table C2. Length change measurements (% expansion) for mortar mix 2 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	4/17/2008								
Immersed	4/21/2008								
Week 1	4/28/2008	0.01	0.01	0.01	0.01	0.01	0.02	0.009	0.003
Week 2	5/5/2008	0.01	0.01	0.01	0.01	0.01	0.02	0.012	0.005
Week 3	5/12/2008	0.01	0.01	0.01	0.02	0.01	0.02	0.013	0.004
Week 4	5/19/2008	0.01	0.01	0.01	0.02	0.01	0.01	0.011	0.003
Week 8	6/16/2008	0.01	0.02	0.01	0.02	0.02	0.02	0.016	0.005
Week 13	7/21/2008	0.01	0.02	0.02	0.03	0.03	0.02	0.023	0.009
Week 15	8/4/2008	0.01	0.03	0.02	0.04	0.05	0.02	0.027	0.014
Month 4	8/24/2008								
Month 6	10/21/2008	0.00	0.06	0.03	0.10	0.10	0.01	0.049	0.042
Month 9	1/20/2009	0.04	0.16	0.08	0.27	0.27	0.02	0.139	0.111
Month 12	4/22/2009	0.09	0.35	0.20			0.02	0.163	0.142

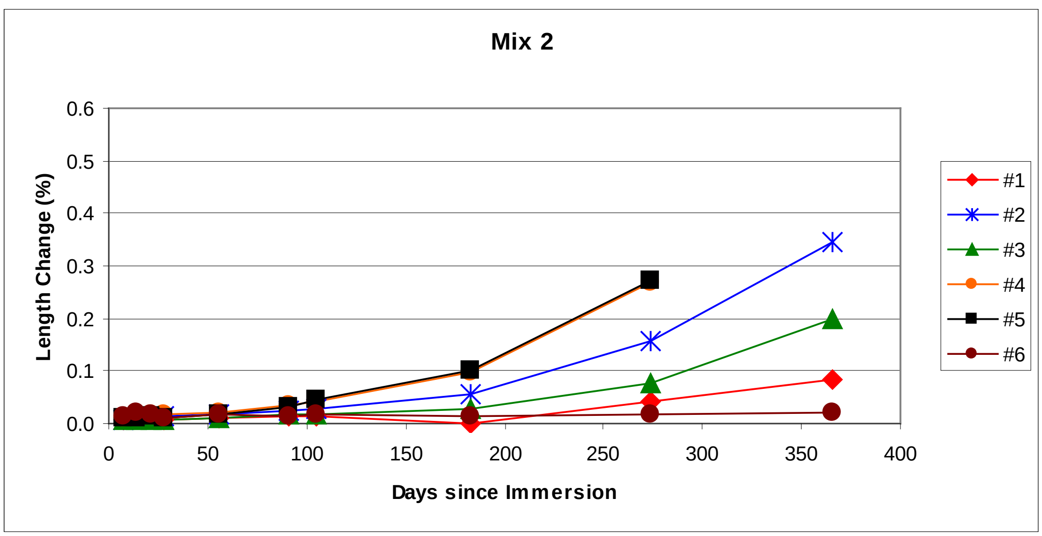

Figure C2. Length change vs. time of exposure for mortar mix 2

Table C3. Length change measurements (% expansion) for mortar mix 3 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	Average	Std. Dev.
Cast	4/22/2008							
Immersed	4/25/2008							
Week 1	5/2/2008	0.00	0.00	0.02	0.02	0.01	0.009	0.009
Week 2	5/9/2008	0.01	0.00	0.01	0.01	0.01	0.009	0.006
Week 3	5/16/2008	0.01	0.00	0.01	0.01	0.01	0.007	0.005
Week 4	5/23/2008							
Week 8	6/20/2008	0.02	0.00	0.02	0.02	0.01	0.014	0.015
Week 13	7/25/2008	0.02	0.01	0.02	0.02	0.02	0.018	0.006
Week 15	8/8/2008	0.02	0.01	0.03	0.03	0.02	0.021	0.005
Month 4	8/28/2008							
Month 6	10/25/2008	0.02	0.01	0.02	0.02	0.02	0.020	0.004
Month 9	1/24/2009	0.03	0.02	0.03	0.03	0.03	0.027	0.005
Month 12	4/26/2009		0.06	0.03	0.04	0.06	0.047	0.014

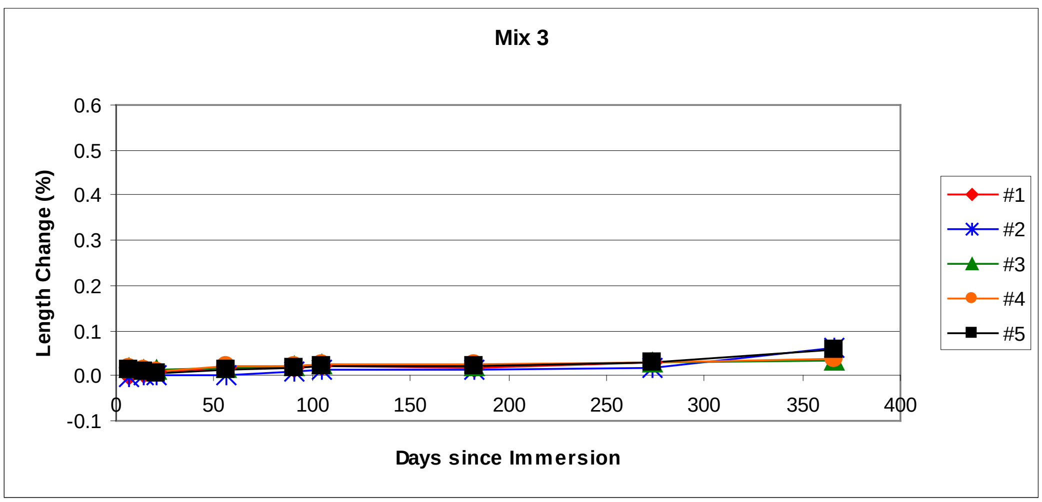

Figure C3. Length change vs. time of exposure for mortar mix 3.

Table C4. Length change measurements (% expansion) for mortar mix 4 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	4/24/2008								
Immersed	4/25/2008								
Week 1	5/2/2008	0.01	0.00	0.02	0.02	0.00	0.01	0.008	0.006
Week 2	5/9/2008	0.01	0.00	0.01	0.01	0.00	0.01	0.007	0.004
Week 3	5/16/2008	0.01	0.00	0.01	0.01	0.00	0.01	0.004	0.004
Week 4	5/23/2008	0.01	0.00	0.01	0.01	0.00	0.01	0.005	0.004
Week 8	6/20/2008	0.01	0.00	0.01	0.01	0.01	0.01	0.008	0.004
Week 13	7/25/2008	0.01	0.01	0.01	0.02	0.02	0.02	0.014	0.003
Week 15	8/8/2008	0.02	0.02	0.01	0.02	0.02	0.02	0.017	0.002
Month 4	8/28/2008								
Month 6	10/25/2008	0.02	0.01	0.02	0.02	0.02	0.02	0.017	0.004
Month 9	1/24/2009	0.02	0.01	0.02	0.04	0.02	0.02	0.020	0.009
Month 12	4/29/2009	0.02	0.01	0.02	0.02	0.02	0.02	0.019	0.007

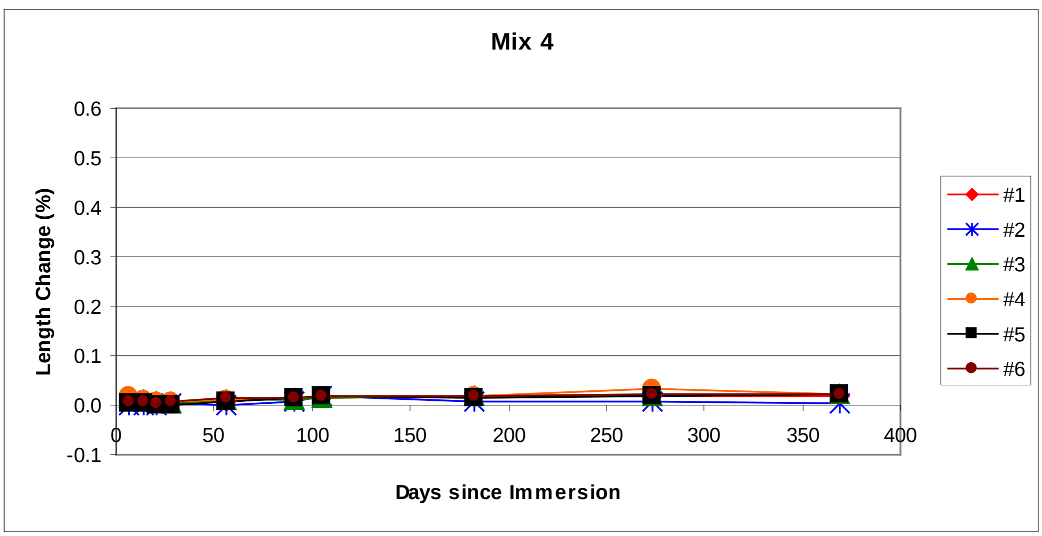

Figure C4. Length change vs. time of exposure for mortar mix 4.

Table C5. Length change measurements (% expansion) for mortar mix 5 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	4/24/2008								
Immersed	4/25/2008								
Week 1	5/2/2008	0.02	0.01	0.01	0.01	0.01	0.02	0.013	0.004
Week 2	5/9/2008	0.02	0.01	0.01	0.02	0.02	0.02	0.015	0.003
Week 3	5/16/2008	0.03	0.03	0.02	0.03	0.02	0.03	0.026	0.006
Week 4	5/23/2008	0.02	0.02	0.02	0.02	0.02	0.02	0.021	0.002
Week 8	6/20/2008	0.03	0.02	0.02	0.02	0.02	0.02	0.023	0.003
Week 13	7/25/2008								
Week 15	8/8/2008								
Month 4	8/28/2008								
Month 6	10/25/2008								
Month 9	1/26/2009								
Month 12	4/26/2009								

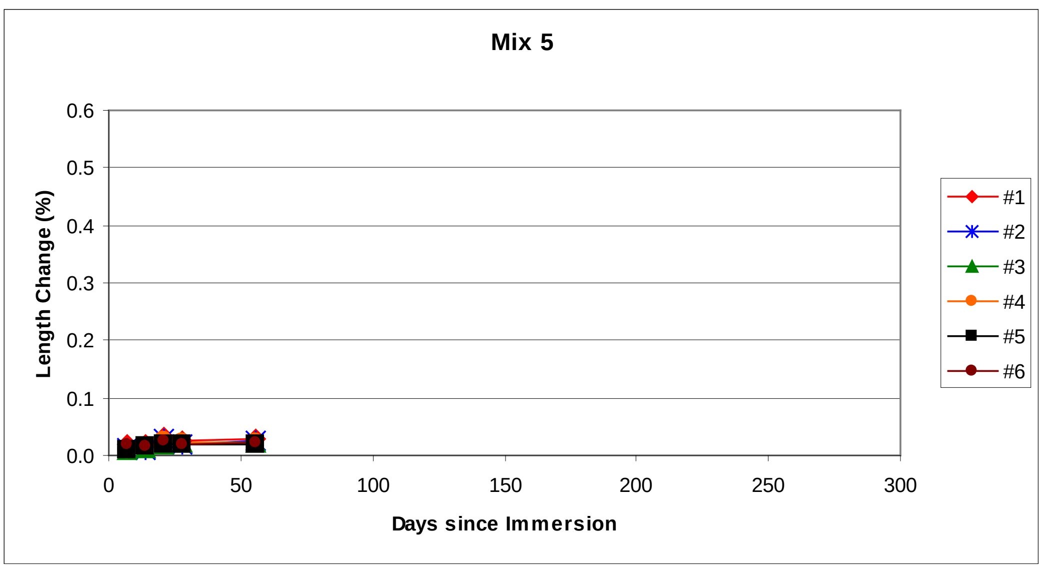

Figure C5. Length change vs. time of exposure for mortar mix 5.

Table C6. Length change measurements (% expansion) for mortar mix 6 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	5/6/2008								
Immersed	5/7/2008								
Week 1	5/14/2008	0.00	-0.01	-0.01	0.00	0.00	0.00	-0.002	0.004
Week 2	5/21/2008	0.00	0.00	0.00	0.01	0.00	0.01	0.003	0.004
Week 3	5/28/2008	0.01	0.00	0.00	0.01	0.00	0.01	0.005	0.004
Week 4	6/4/2008	0.01	0.00	0.00	0.00	0.00	0.01	0.004	0.004
Week 8	7/2/2008	0.02	0.01	0.00	0.02	0.01	0.01	0.009	0.007
Week 13	8/6/2008	0.03	0.02	0.01	0.02	0.02	0.02	0.021	0.004
Week 15	8/1/2008	0.03	0.02	0.02	0.03	0.02	0.03	0.025	0.005
Month 4	9/9/2008	0.04	0.03	0.02	0.04	0.03	0.04	0.035	0.009
Month 6	11/6/2008	0.10	0.09	0.05	0.11	0.09	0.11	0.092	0.021
Month 9	2/5/2009	0.25	0.24	0.17	0.31	0.25	0.29	0.252	0.051
Month 12	5/8/2009	0.42	0.42	0.30	0.54	0.42	0.50	0.434	0.080

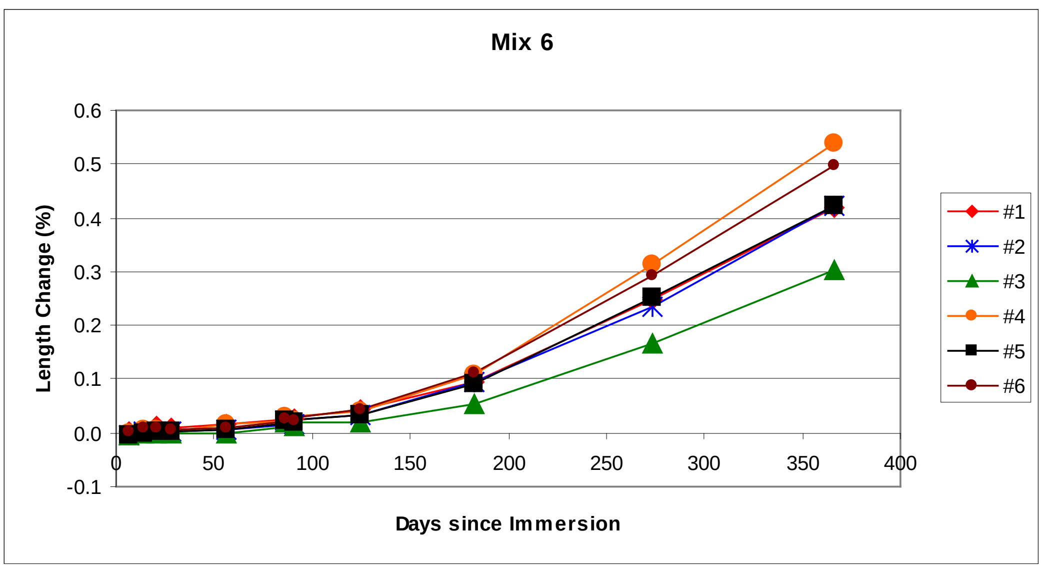

Figure C6. Length change vs. time of exposure for mortar mix 6.

Table C7. Length change measurements (% expansion) for mortar mix 7 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	5/6/2008								
Immersed	5/8/2008								
Week 1	5/15/2008	0.01	0.00	0.00	-0.01	0.00	0.01	0.002	0.004
Week 2	5/22/2008	0.01	0.00	0.00	0.00	0.01	0.01	0.004	0.004
Week 3	5/29/2008	0.01	0.00	0.00	0.00	0.00	0.00	0.001	0.003
Week 4	6/5/2008	0.01	0.00	0.01	0.00	0.01	0.01	0.005	0.003
Week 8	7/3/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.011	0.003
Week 13	8/7/2008	0.02	0.02	0.02	0.01	0.02	0.01	0.016	0.005
Week 15	8/21/2008	0.02	0.02	0.02	0.01	0.02	0.02	0.020	0.003
Month 4	9/10/2008	0.02	0.02	0.02	0.01	0.02	0.02	0.019	0.004
Month 6	11/7/2008	0.03	0.02	0.03	0.01	0.02	0.02	0.022	0.005
Month 9	2/6/2009	0.04	0.03	0.03	0.02	0.03	0.03	0.027	0.006
Month 12	5/9/2009	0.04	0.04	0.04	0.02	0.03	0.03	0.034	0.006

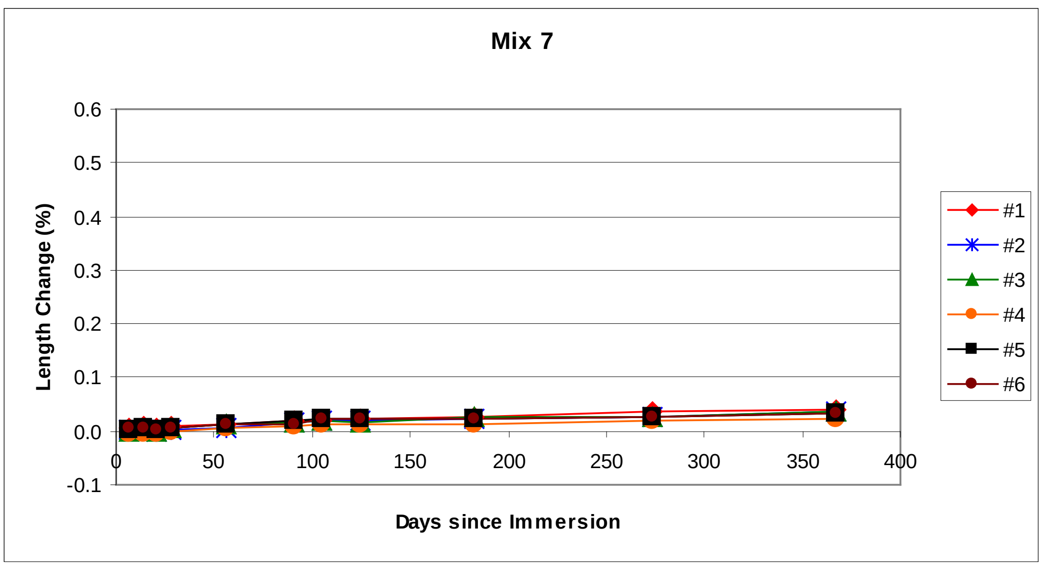

Figure C7. Length change vs. time of exposure for mortar mix 7.

Table C8. Length change measurements (% expansion) for mortar mix 8 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	Average	Std. Dev.
Cast	5/8/2008							
Immersed	5/12/2008							
Week 1	5/19/2008	0.01	0.01	0.01	0.01	0.00	0.009	0.003
Week 2	5/26/2008	0.01	0.01	0.01	0.01	0.00	0.009	0.003
Week 3	6/2/2008	0.02	0.01	0.01	0.01	0.01	0.011	0.004
Week 4	6/9/2008	0.02	0.01	0.02	0.01	0.01	0.012	0.005
Week 8	7/8/2008	0.02	0.01	0.02	0.02	0.01	0.014	0.003
Week 13	8/11/2008	0.02	0.02	0.02	0.02	0.01	0.019	0.003
Week 15	8/25/2008	0.02	0.02	0.02	0.02	0.01	0.018	0.004
Month 4	9/19/2008	0.02	0.02	0.02	0.01	0.01	0.015	0.004
Month 6	11/8/2008	0.02	0.02	0.02	0.02	0.01	0.018	0.004
Month 9	2/7/2009	0.03	0.02	0.02	0.02	0.02	0.021	0.004
Month 12	5/10/2009	0.03	0.02	0.02	0.02	0.02	0.023	0.004

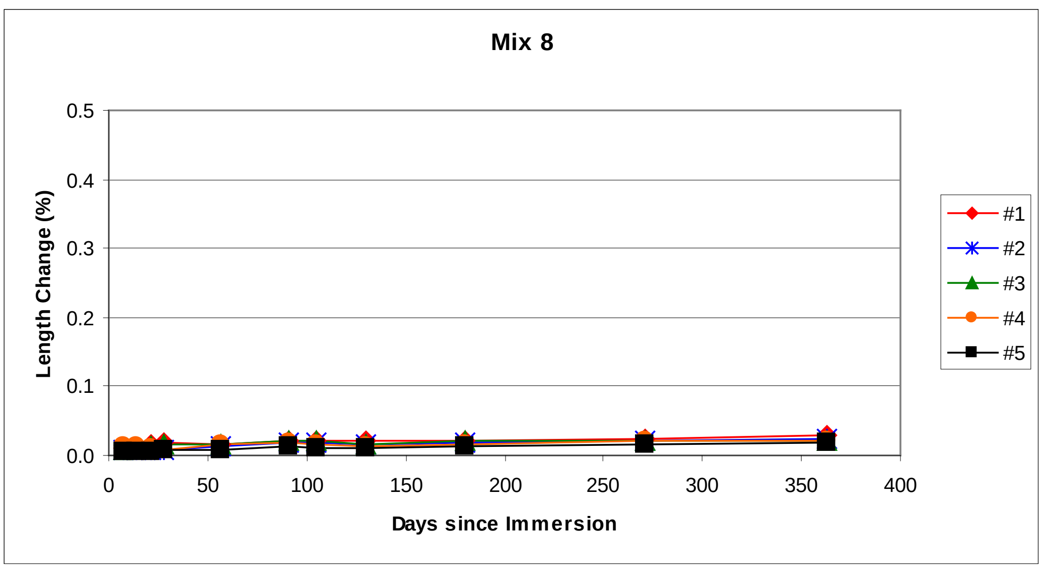

Figure C8. Length change vs. time of exposure for mortar mix 8.

Table C9. Length change measurements (% expansion) for mortar mix 9 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	Average	Std. Dev.
Cast	5/8/2008							
Immersed	5/9/2008							
Week 1	5/16/2008	0.00	0.00	0.01	0.00	0.00	0.001	0.004
Week 2	5/23/2008	0.00	0.00	0.01	-0.01	0.00	0.001	0.004
Week 3	5/30/2008	0.00	0.01	0.01	0.00	0.01	0.005	0.005
Week 4	6/6/2008	0.00	0.00	0.01	0.00	0.01	0.005	0.002
Week 8	7/3/2008	0.00	0.01	0.01	0.00	0.01	0.006	0.004
Week 13	8/8/2008	0.01	0.01	0.01	0.00	0.01	0.009	0.004
Week 15	8/22/2008	0.00	0.01	0.02	0.01	0.01	0.009	0.004
Month 4	9/14/2008	0.00	0.01	0.01	0.00	0.01	0.008	0.004
Month 6	11/11/2008	0.01	0.01	0.01	0.01	0.01	0.008	0.002
Month 9	2/10/2009	0.01	0.01	0.01	0.01	0.01	0.011	0.003
Month 12	5/13/2009	0.01	0.01	0.02	0.01	0.02	0.013	0.003

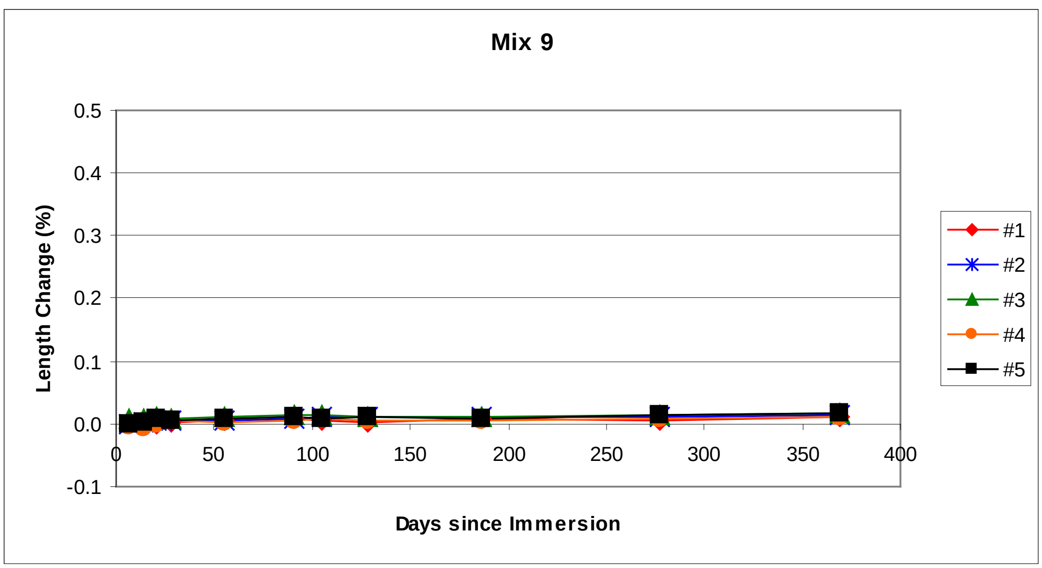

Figure C9. Length change vs. time of exposure for mortar mix 9.

Table C10. Length change measurements (% expansion) for mortar mix 10 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	5/12/2008								
Immersed	5/12/2008								
Week 1	5/20/2008	0.01	0.00	0.00	0.00	0.01	0.01	0.004	0.002
Week 2	5/27/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.010	0.001
Week 3	6/3/2008	0.01	0.01	0.01	0.02	0.01	0.01	0.012	0.003
Week 4	6/10/2008	0.02	0.01	0.01	0.02	0.01	0.03	0.015	0.003
Week 8	7/8/2008	0.02	0.02	0.02	0.02	0.02	0.02	0.019	0.002
Week 13	8/12/2008	0.03	0.03	0.03	0.03	0.03	0.03	0.027	0.001
Week 15	8/26/2008	0.03	0.02	0.03	0.03	0.03	0.03	0.026	0.002
Month 4	9/15/2008	0.03	0.02	0.03	0.03	0.03	0.03	0.028	0.002
Month 6	11/12/2008	0.04	0.02	0.06	0.05	0.06	0.06	0.049	0.017
Month 9	2/11/2009	0.15	0.22	0.39	0.31	0.44	0.43	0.322	0.119
Month 12	5/14/2009								

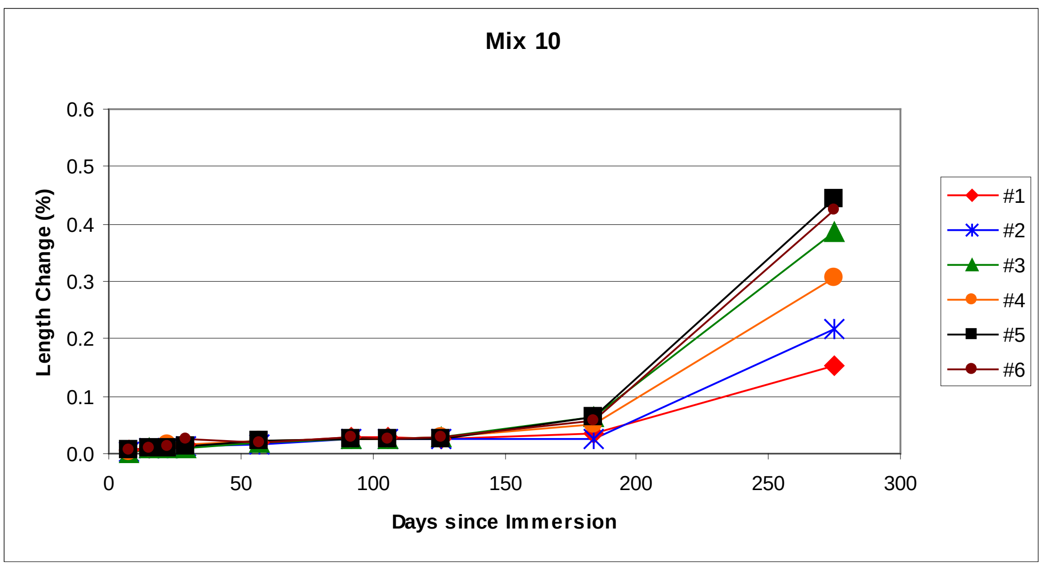

Figure C10. Length change vs. time of exposure for mortar mix 10.

Table C11. Length change measurements (% expansion) for mortar mix 11 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	5/20/2008								
Immersed	5/22/2008								
Week 1	5/29/2008	0.01	0.00	0.01	0.01	0.01	0.01	0.005	0.005
Week 2	6/5/2008	0.01	-0.01	0.01	0.01	0.01	0.01	0.005	0.006
Week 3	6/12/2008	0.01	0.01	0.01	0.01	0.01	0.02	0.010	0.002
Week 4	6/19/2008	0.01	0.01	0.01	0.02	0.01	0.01	0.012	0.003
Week 8	7/17/2008	0.02	0.02	0.02	0.02	0.02	0.02	0.018	0.002
Week 13	8/21/2008	0.02	0.02	0.03	0.02	0.03	0.03	0.025	0.002
Week 15	9/5/2008	0.03	0.03	0.03	0.03	0.03	0.03	0.027	0.001
Month 4	9/22/2008	0.02	0.03	0.03	0.03	0.03	0.03	0.027	0.002
Month 6	11/20/2008	0.03	0.04	0.03	0.03	0.03	0.04	0.034	0.002
Month 9	2/19/2009	0.05	0.06	0.05	0.05	0.05	0.05	0.051	0.003
Month 12	5/22/2009	0.07	0.09	0.08	0.08	0.08	0.09	0.079	0.008

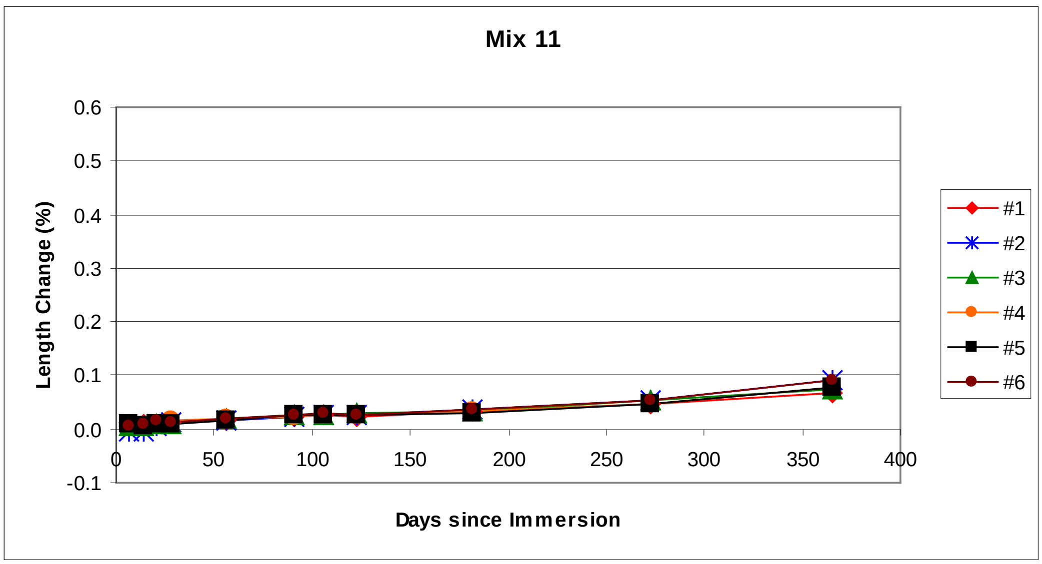

Figure C11. Length change vs. time of exposure for mortar mix 11.

Table C12. Length change measurements (% expansion) for mortar mix 12 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	5/20/2008								
Immersed	5/22/2008								
Week 1	5/29/2008	0.00	0.01	0.01	0.01	0.00	0.01	0.007	0.006
Week 2	6/5/2008	0.00	0.01	0.01	0.02	0.01	0.02	0.011	0.006
Week 3	6/12/2008	0.01	0.02	0.02	0.02	0.01	0.02	0.016	0.006
Week 4	6/19/2008	0.01	0.02	0.02	0.02	0.02	0.02	0.019	0.006
Week 8	7/17/2008	0.01	0.03	0.03	0.03	0.02	0.03	0.024	0.005
Week 13	8/21/2008	0.03	0.03	0.03	0.04	0.03	0.04	0.033	0.003
Week 15	9/5/2008	0.02	0.04	0.03	0.04	0.03	0.04	0.033	0.007
Month 4	9/22/2008	0.02	0.03	0.04	0.04	0.03	0.04	0.032	0.007
Month 6	11/20/2008	0.02	0.04	0.05	0.04	0.04	0.05	0.039	0.010
Month 9	2/19/2009	0.03	0.04	0.04	0.07	0.07	0.07	0.053	0.017
Month 12	5/22/2009	0.05	0.07		0.12	0.19	0.13	0.112	0.055

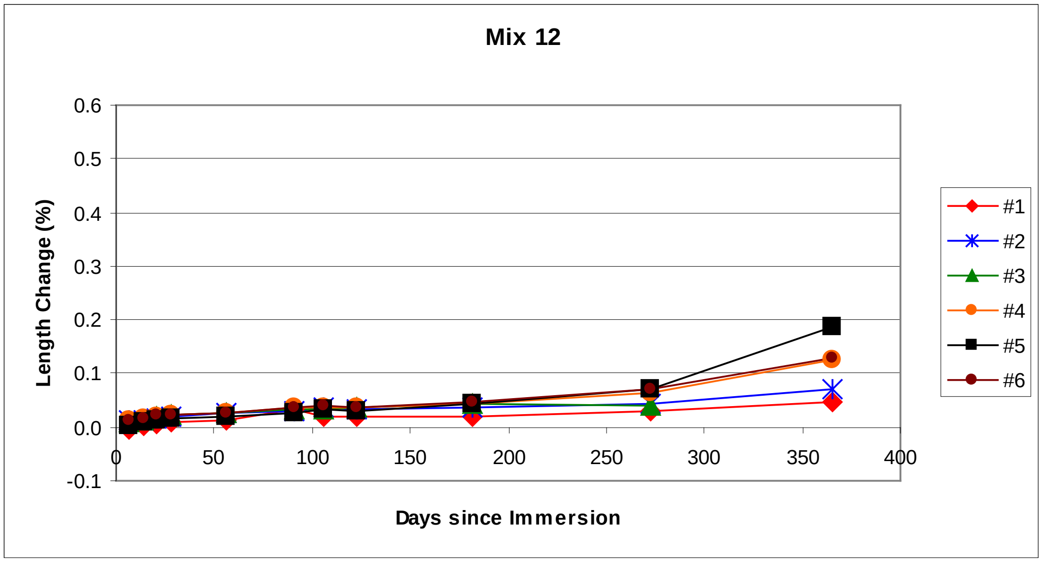

Figure C12. Length change vs. time of exposure for mortar 12.

Table C13. Length change measurements (% expansion) for mortar mix 13 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	Average	Std. Dev.
Cast	5/28/2008							
Immersed	6/2/2008							
Week 1	6/9/2008	0.01	0.00	0.00	0.00	0.00	0.003	0.002
Week 2	6/16/2008	0.01	0.00	0.01	0.00	0.01	0.005	0.002
Week 3	6/23/2008	0.01	0.01	0.01	0.01	0.01	0.008	0.002
Week 4	6/30/2008	0.01	0.01	0.01	0.01	0.01	0.007	0.002
Week 8	7/28/2008	0.02	0.01	0.02	0.01	0.02	0.014	0.003
Week 13	9/2/2008	0.02	0.01	0.02	0.02	0.02	0.017	0.003
Week 15	9/15/2008	0.02	0.01	0.02	0.02	0.02	0.017	0.003
Month 4	10/5/2008	0.01	0.01	0.01	0.01	0.01	0.008	0.002
Month 6	12/2/2008	0.02	0.01	0.02	0.01	0.02	0.015	0.002
Month 9	3/3/2009	0.02	0.01	0.02	0.02	0.02	0.016	0.002
Month 12	6/3/2009	0.02	0.02	0.02	0.02	0.02	0.020	0.003

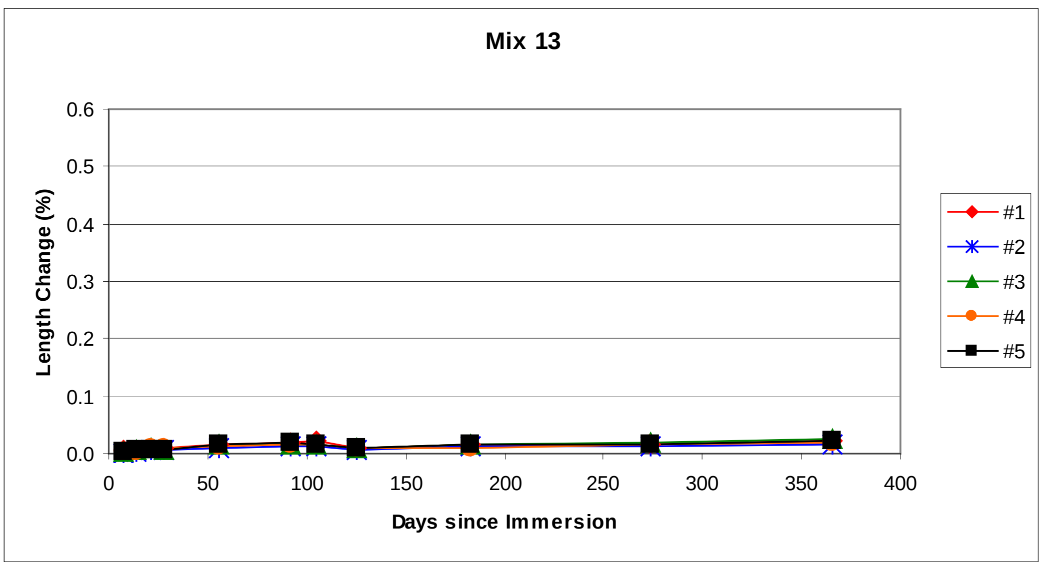

Figure C13. Length change vs. time of exposure for mortar mix 13.

Table C14. Length change measurements (% expansion) for mortar mix 14 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	5/28/2008								
Immersed	5/29/2008								
Week 1	6/5/2008	0.00	0.01	0.00	0.00	0.00	0.00	0.002	0.002
Week 2	6/12/2008	0.01	0.01	0.00	0.01	0.00	0.00	0.004	0.003
Week 3	6/19/2008	0.01	0.00	0.00	0.01	0.00	0.00	0.004	0.002
Week 4	6/26/2008	0.00	0.01	0.00	0.01	0.00	0.00	0.003	0.002
Week 8	7/24/2008	0.01	0.02	0.01	0.01	0.01	0.00	0.011	0.002
Week 13	8/28/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.011	0.002
Week 15	9/11/2008	0.01	0.01	0.01	0.01	0.01	0.01	0.012	0.002
Month 4	10/1/2008	0.01	0.01	0.01	0.01	0.02	0.01	0.010	0.003
Month 6	11/28/2008	0.01	0.01	0.01	0.01	0.01	0.00	0.010	0.001
Month 9	2/27/2009	0.01	0.02	0.01	0.02	0.02	0.01	0.014	0.002
Month 12	5/30/2009	0.01	0.02	0.01	0.02	0.01	0.01	0.013	0.003

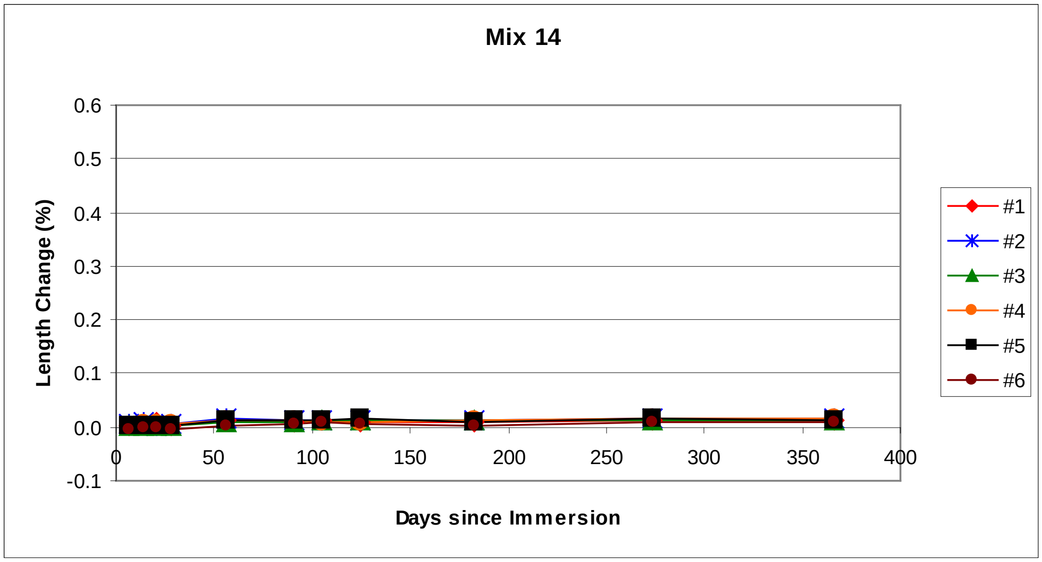

Figure C14. Length change vs. time of exposure for mortar mix 14.

Table C15. Length change measurements (% expansion) for mortar mix 15 according to ASTM C1012.

Age	Date	#1	#2	#3	#4	#5	#6	Average	Std. Dev.
Cast	6/4/2008								
Immersed	6/5/2008								
Week 1	6/12/2008								
Week 2	6/19/2008	0.01	0.01	0.01	0.00	0.00	0.00	0.005	0.004
Week 3	6/26/2008	0.01	0.01	0.01	0.00	0.00	0.01	0.008	0.003
Week 4	7/3/2008	0.01	0.01	0.01	0.01	0.00	0.01	0.009	0.004
Week 8	7/31/2008	0.02	0.02	0.02	0.01	0.01	0.01	0.013	0.004
Week 13	9/5/2008	0.02	0.00	0.02	0.01	0.01	0.03	0.015	0.007
Week 15	9/18/2008	0.02	0.01	0.01	0.01	0.01	0.01	0.013	0.002
Month 4	10/8/2008	0.02	0.02	0.01	0.01	0.01	0.02	0.014	0.003
Month 6	12/5/2008	0.02	0.02	0.02	0.01	0.01	0.02	0.016	0.004
Month 9	3/6/2009	0.04	0.03	0.02	0.01	0.02	0.02	0.023	0.009
Month 12	6/6/2009	0.05	0.04	0.03	0.02	0.02	0.03	0.031	0.013

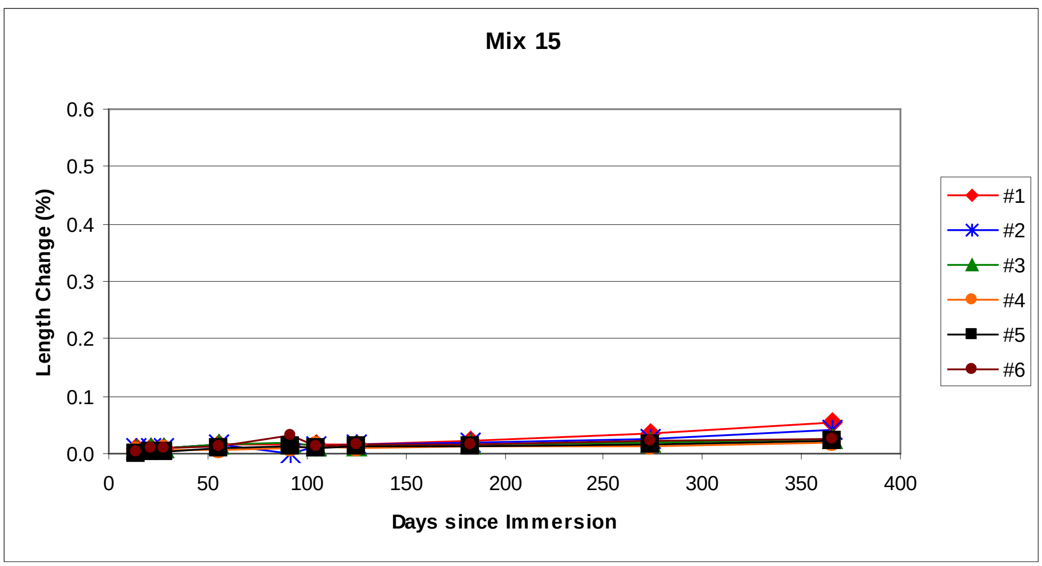

Figure C15. Length change vs. time of exposure for mortar mix 15.

Appendix D: ASTM C1012 Photographs

Figure D1. Bars of mortar mix 1 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D2. Bars of mortar mix 2 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D3. Bars of mortar mix 3 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D4. Bars of mortar mix 4 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D5. Bars of mortar mix 5 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D6. Bars of mortar mix 6 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D7. Bars of mortar mix 7 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D8. Bars of mortar mix 8 after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D9. Bars of mortar mix 9 after exposure to sulfate solution for over 1 year according to ASTM C1012.

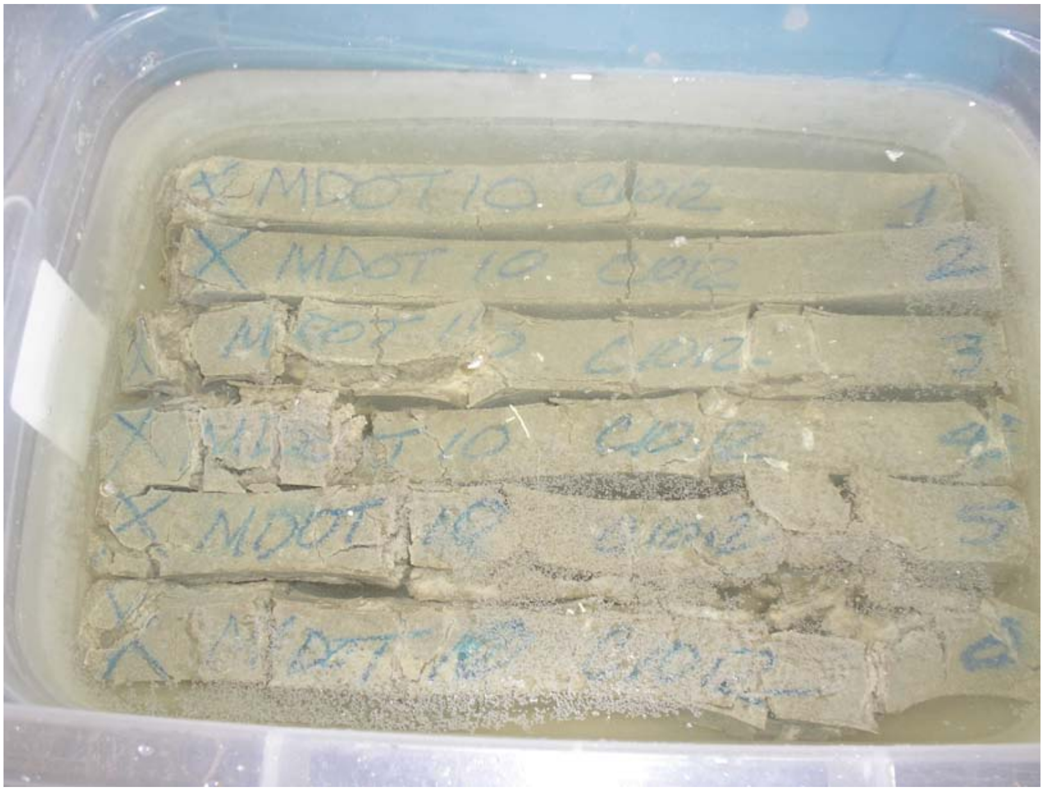

Figure D10. Bars of mortar mix 10 after exposure to sulfate solution for over 1 year according to ASTM C1012.

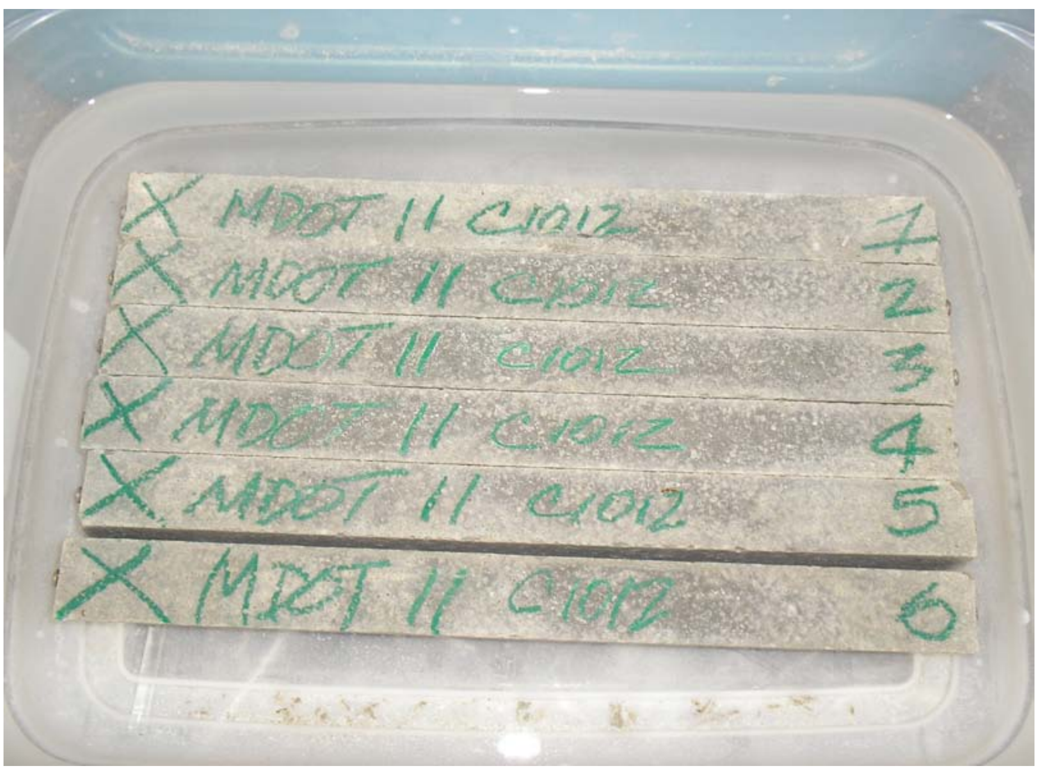

Figure D11. Bars of mortar mix 11 after exposure to sulfate solution for over 1 year according to ASTM C1012.

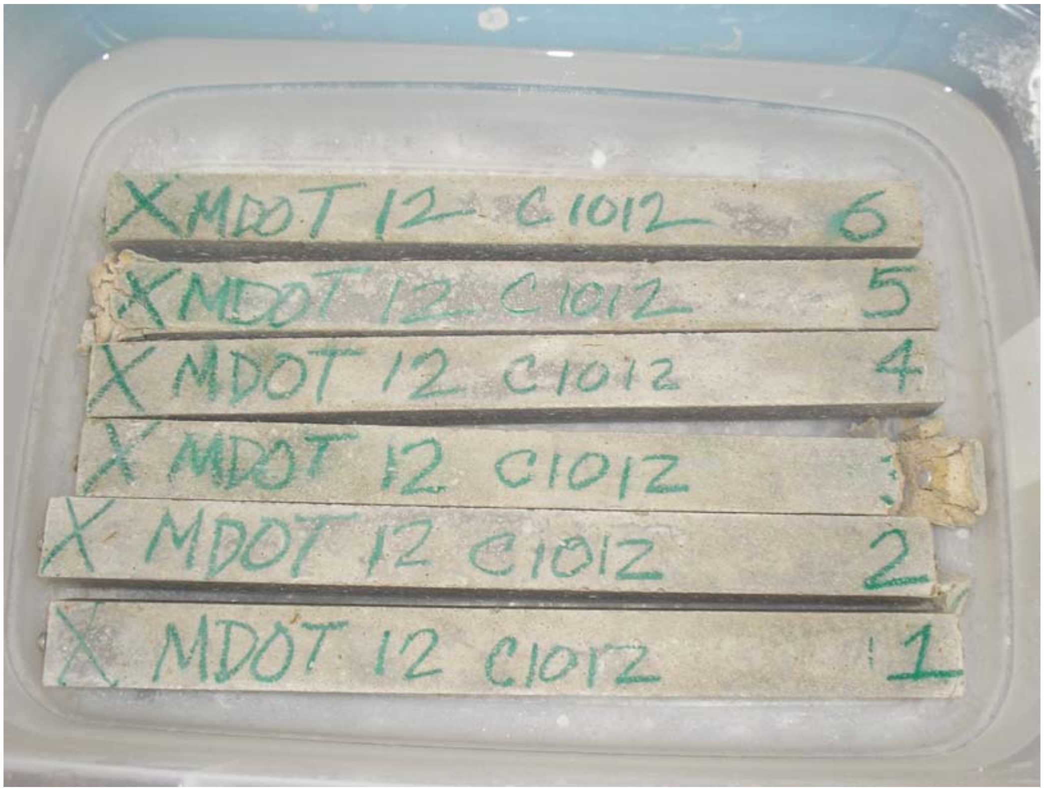

Figure D12. Bars of mortar mix 12 after exposure to sulfate solution for over 1 year according to ASTM C1012.

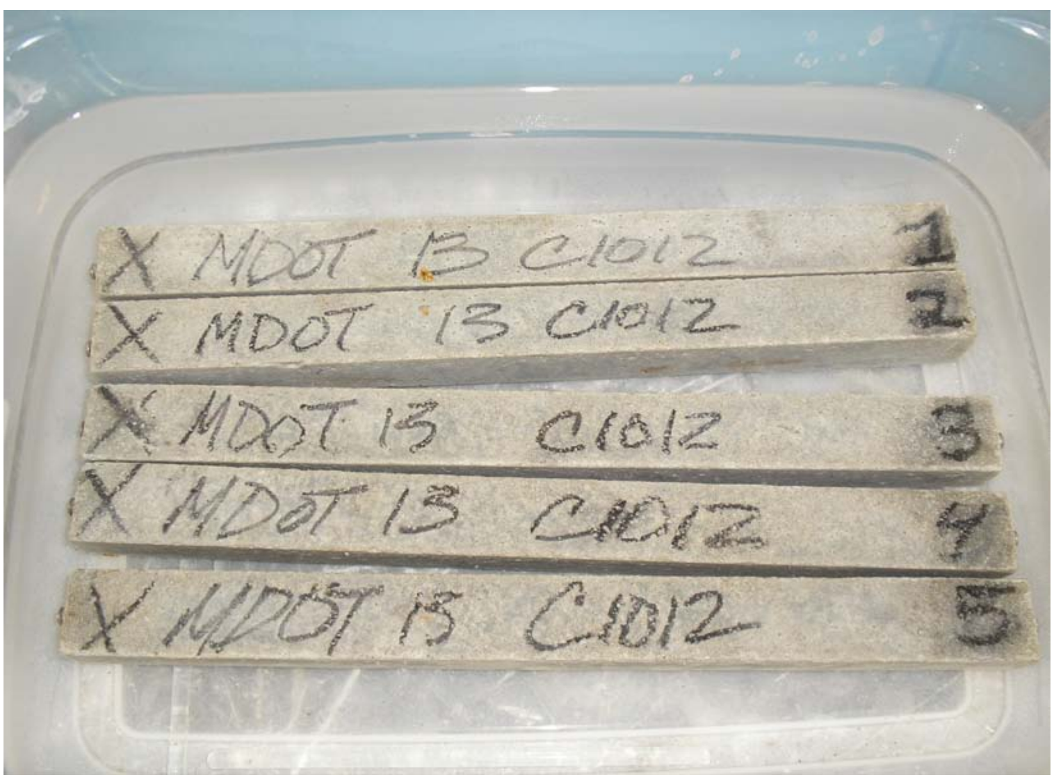

Figure D13. Bars of mortar mix 13 after exposure to sulfate solution for over 1 year according to ASTM C1012.

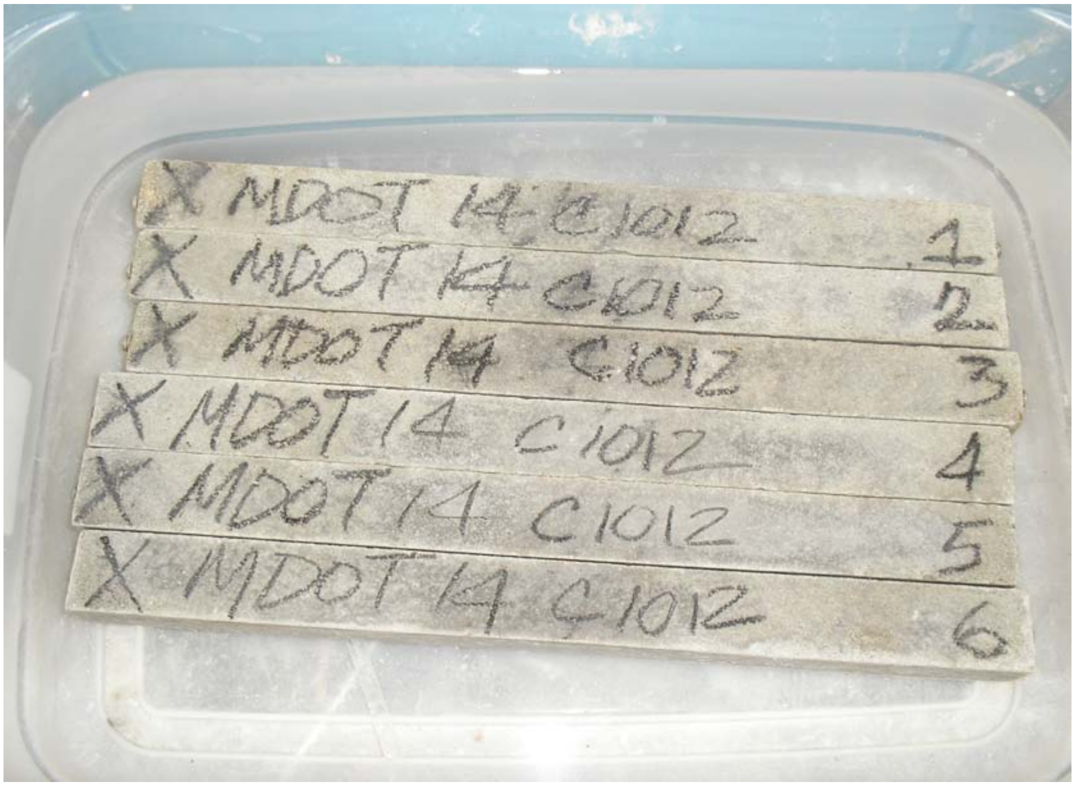

Figure D14. Bars of mortar mix 14 e after exposure to sulfate solution for over 1 year according to ASTM C1012.

Figure D15. Bars of mortar mix 15 after exposure to sulfate solution for over 1 year according to ASTM C1012.

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14. ABSTRACT

At some construction sites in Mississippi, deterioration of concrete in contact with the surrounding soil could be related to the high sulfate content of the adjacent soils. Studies dating to 1966 have documented sulfate attack associated with specific types of sulfide or sulfate-rich soils. Future highway-related construction must include specified procedures and materials that will ensure the service life of concrete construction is not reduced by such aggressive soils.

In this project, three portland cements and five pozzolans, which can be used as cement replacements, were investigated to determine which of these cements and/or cement blends could be categorized as sulfate-resistant. Two screening procedures, the University of California Pavement Research Center's Caltrans rapid sulfate test and the American Society for Testing and Materials' Standard C1012 (standard test method for length change), were used to evaluate the cements/blended cements. Results from the Caltrans test identified only one of the blended cements investigated that failed to qualify as sulfate resistant. The results from the bar expansion test (ASTM C1012) indicated that only one cement evaluated would not meet the criterion for an American Concrete Institute (ACI) Class 1 sulfate-resistant cement.

(Continued)

15. SUBJECT TERMS

Acid attack	Silica fume	Sulfate attack
Metakaolin	Slag	

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
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14. ABSTRACT (Concluded)

Further screening was done by examining the expansion trends and the conditions of the test bars after 1 year. Eight cements or blended cements could be judged on the basis of no or slow tendency to show change dimensions and no discernible damage to the mortar test bars after 1 year of exposure. All of the cements performed well in this test program when blended with silica fume.